Spaceborne GNSS Radio Occultation Instrumentation for Operational Applications

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ABSTRACT

Radio occultation (RO) instruments using GNSS signals are specialised spaceborne receivers designed to provide highly accurate measurements from which one can derive vertical profiles of the temperature, pressure and humidity in the atmosphere, as well as profiles of electron content in the ionosphere. A family of operational RO instruments is being developed for a number of European space projects since 1996. The basic functions of the instrument include: reception of signals that have crossed the atmosphere at varying altitudes by means of two antenna arrays; acquisition of such signals, also during the rise (ascending) RO events, when a signal first appears after crossing dense tropospheric layers causing large dynamics in amplitude and phase; robust signal tracking to provide precise amplitude and phase measurements; on-board processing to support RO event predictions, also to aid the tracking. We summarise the main requirements and illustrate the main technical features adopted. The expected performance is also presented.

INTRODUCTION

The use of navigation signals to determine properties of the Earth's atmosphere by means of the radio occultation (RO) technique has come a long way from the initial proposals made in the Eighties by Russian and US scientists [1, 2]. As widely described in the literature (see e.g. [3–5]), this remote sensing technique uses refraction angle measurements of navigation signal paths, collected from special receivers orbiting the Earth, to retrieve vertical profiles of temperature, pressure and humidity in the (neutral) atmosphere and electron content of the ionosphere with unprecedented accuracy and resolution.

Until the mid-Nineties, despite the very promising theoretical analyses and the results of a long history of RO research for planetary exploration, there existed considerable scepticism about the possibility to meet the demanding Earth observation requirements with the RO technique. The launch of the GPS/MET experiment on the Microlab-1 satellite in April 1995, and the subsequent spate of research confirming the original claims for the measurement quality, marked the turning point for its full acceptance. In this respect, the University Corporation for Atmospheric Research (UCAR), that set up and ran GPS/MET, should be credited for their open data policy and support of international cooperation. These allowed researchers around the world to study ways of processing the RO data as well as the characteristics of temperature and humidity profiles derived from actual measurements.

In Europe, the interest in exploiting GNSS RO data for operational meteorology and climate monitoring rose quickly as scientists re-processed the GPS/MET data in a series of ESA studies. These led to a proposal for a constellation of 12 micro-satellites [7], each carrying a specialised GNSS Receiver for Atmospheric Sounding (GRAS), within the context of ESA's Earth Explorer missions. A constellation is the natural response to the requirements as formulated by an advisory group formed by meteorologists and atmospheric scientists and summarised in Tables 1 and 2. The large set of measurements that a constellation could supply is needed to achieve, after proper temporal and spatial averaging, the accuracy required for the climate monitoring. Although in the highly competitive selection process for the first Earth Explorer missions the proposal was not retained, a strong endorsement of the technique was obtained. GNSS RO was recognised as a new important atmospheric sensing tool because of some key advantages: all-weather capability (no blockage by clouds, unlike classical sounders); high vertical resolution (from ~1.5 km in the stratosphere to ~0.2 km in the troposphere); good accuracy of the retrieved temperature (~1 K); and long-term consistency. The latter quality is essential for climate change monitoring and stems from two factors: the measurements are essentially time-interval measurements, referable to fundamental metrological standards (atomic time); all RO events start or end above the atmosphere, where refraction is null, enabling the removal of residual biases in post-processing.

Table 1: Operational meteorology requirements

		Temperature	Humidity
Horizontal Domain		Global	Global
Horizontal Sampling		< 300 km	< 300 km
Vertical Resolution		0.5-1.0 km	0.5 km
Time Resolution		1-6 hrs	1-6 hrs
Absolute Accuracy	0 - 30 km	< 1.0 K	Max{10 %, 0.2 g/kg}
	30 - 50km	< 2 K	n/a
Timeliness		2-3 hrs	2-3 hrs

Table 2: Climate monitoring requirements

		Temperature	Humidity
Horizontal Domain		Global	Global
Horizontal Sampling		2.5° * 2.5°	2.5° * 2.5°
Vertical Domain		> 1 hPa (0-50 km)	> 300 hPa (0-10 km)
Vertical Resolution	Tropo-sphere	0.5 km	0.5 km
	Strato-sphere	1.0 km	n/a
Time Domain		> 10 years	> 10 years
Time Resolution		1 month	1 month
Absolute Accuracy	Tropo-sphere	< 0.2 K	< 3 %
	Strato-sphere	< 0.2 K	n/a
Long Term Stability		< 0.1 K/decade	< 2 %/decade
Timeliness		1-2 months	1-2 months

The relevant space receiver work in Europe started with the development of laboratory breadboards at the Institute of Navigation of the University of Leeds (UK) [8], initially for generic in-orbit scientific applications. ESA then awarded a development contract to Saab Ericsson Space (SE) and its subsidiary Austrian Aerospace (AAe) to develop GRAS prototypes, building upon the previous breadboard work, particularly in the area of digital signal processing and acquisition/tracking firmware. SE is responsible for system and RF design, while AAe is responsible for signal processors and flight S/W.

Given the existing GPS/MET results and those anticipated from planned follow-up experiments (some currently flying, like those on the Oersted and CHAMP missions), the emphasis was not on developing an experimental receiver but rather on producing a space-qualified instrument for future RO operational applications. This proved timely, since in 1997 the European Organisation for the Exploitation of Meteorological Satellites (Eumetsat) decided to include such a RO instrument in the meteorological payload of the three MetOp polar-orbiting satellites (Figure 1). These satellites are jointly developed by ESA and Eumetsat and will be placed in a polar orbit at 835 km altitude starting with MetOp-1 in 2003, so as to provide observations for a total period of at least 14 years. They will carry several instruments for meteorology and climate studies, including a wind scatterometer, an imaging radiometer and several sounders [9]. ESA has entrusted SE with the development of the three GRAS RO instruments for the MetOp satellites. Data from the instruments will be processed and disseminated to weather forecasters in near-real time. In the case of GRAS, the requirement is for calibrated refraction angle measurements to be delivered to users within 2.25 hours, which puts quite a strain on the ground data processing.

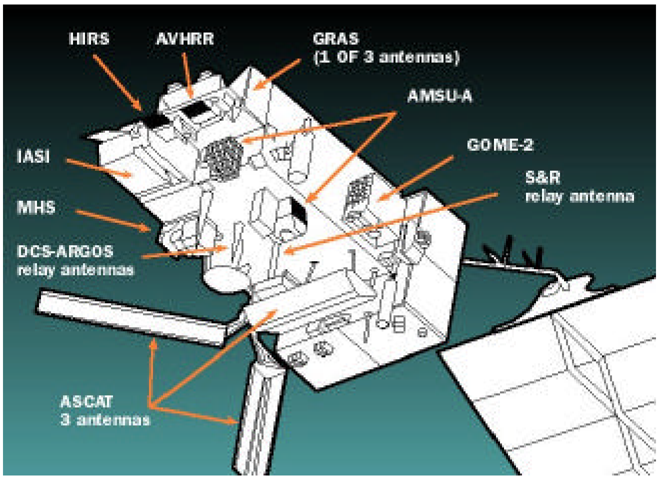

Figure 1: Outline of the instrumentation on MetOp, including the GRAS antenna pointed along the flight direction.

From the mentioned GRAS breadboards, ESA developed a multi-purpose digital ASIC for GNSS applications in space, namely the AGGA (Advanced GPS/GLONASS ASIC) [10, 11]. The AGGA includes the final signal down conversion, C/A and P code generation, de-spreading and integration.

In 1997 SE was also awarded the first of a series of contracts to develop the GPS Occultation Sensor (GPSOS) for the US National Polar Orbiting Environmental Satellite System (NPOESS) [12], which is managed by the Integrated Programme Office (IPO), a joint organisation of the US DoD, NOAA and NASA. The GPSOS development exploits the RO technique also for ionospheric measurements as a primary objective and strongly involves the scientific community. The first NPOESS satellite will be launched in 2008. GPSOS, which is derived from GRAS, uses the same key modules, but differs in that a high degree of redundancy is required. The GPSOS requirements for ionospheric sounding are summarised in Table 3.

Table 3: Operational ionospheric requirements

	Electron Density	Slant Path TEC*)
Horizontal Domain	Global	Global
Vertical Domain	90-800 km	90-800 km
Vertical Resolution	5-20 km	5-20 km
Absolute Accuracy	Max{20 %, 3×10^{-5} cm^{-3}}	3 TEC units

*) TEC Total Electron Content

In the following sections the measurement principle will be outlined briefly, the instrument architecture and the main subsystems will be described, remarking the main features and innovations. This will be followed by a summary of the key performance parameters and finally by remarks on the preparation of a new instrument generation.

MEASUREMENT PRINCIPLE

In a greatly simplified way, the measurement of an RO instrument flying on a LEO can be described as follows. The instrument acquires and tracks the GPS signal at the two frequencies L1 and L2, above the atmosphere. As the ray path descends into the atmosphere, the changes in carrier phase (Doppler) at the two frequencies are recorded, Figure 2. These phase measurements are transmitted to ground for further processing.

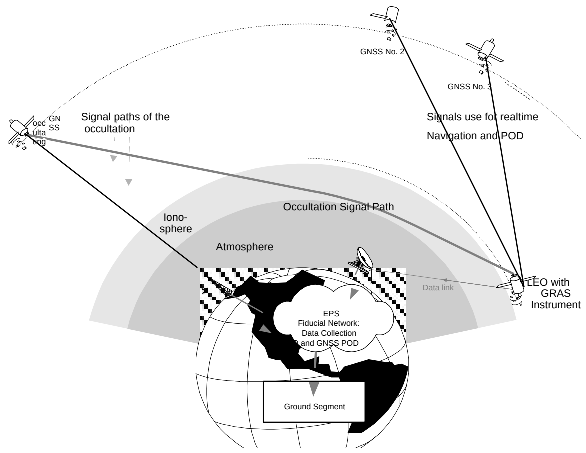

Figure 2: Occultation measurement geometry

Knowing the spacecraft positions and velocities, the Doppler shift provides information on the directions of reception and transmission, Figure 3. In the case of a spherically symmetric atmosphere, the central part of the ray path will be symmetric and the distances from Earth centre to ray asymptotes (so-called impact parameters, *a* in Figure 3) will be equal. The impact parameters and the refraction angle can be derived from the Doppler shift using only the measurement geometry. As a result, the refraction angle, α, can be derived as a function of the impact parameter, *a*, for the two frequencies. The dispersive behaviour of the ionosphere and the non-dispersive behaviour of the neutral atmosphere enable the refraction angle contributions of these two regions to be separated.

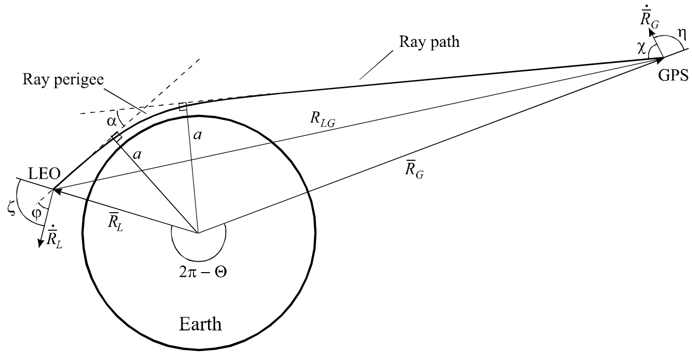

Figure 3: RO geometry showing refraction angle, a, and impact parameter, *a*.

Making use of the symmetric atmosphere condition once more, the refraction index profile as function of the Earth radius is then obtained from an integral transform, the Abel transform (for details see e.g. [3–5]). The refractivity depends on the air pressure, temperature and water vapour content. These parameters are retrieved using the gas equation of state and the hydrostatic equilibrium equation. At low altitudes, the water content of the air dominates the refraction effect. The temperature can then be uniquely determined only at altitudes above 6-8 km, except in cold regions where water vapour is low. At lower altitudes, external temperature information allows one to recover humidity.

Since ionospheric refractivity depends on electron density, electron density profile and TEC can be obtained from RO measurements in the ionosphere with a similar (in fact, simpler) approach.

In order to obtain the required measurement accuracy, corrections have to be made within the ground processing for:

- GNSS clock instabilities: corrections are derived from fiducial ground stations tracking GNSS satellites in parallel with the occultation measurement.
- GNSS SV positions, determined using fiducial station measurements and precise orbit determination (POD) processing
- LEO position, determined using the RO instrument navigation measurements
- Antenna angle of incidence
- Temperature of the instrument ultra-stable oscillator (USO) and of other electronics

INSTRUMENT CHARACTERISTICS

Besides the usual real-time navigation, the instrument must accurately track a sufficient number of GNSS SV's for RO and for POD, providing precise dual-frequency carrier and code phase measurements and, for the RO application, also signal amplitude measurements, in a fully autonomous manner. The key characteristics of an operational instrument like GRAS and GPSOS and the main differences from common receivers can be summarised as follows:

a) number of channels adequate to 'capture' nearly all occultation events, as well as to collect measurements needed for POD
b) two high-gain antennas with shaped beam patterns, pointed in the satellite anti-velocity direction (for set or descending RO events) and in the velocity direction (for rise or ascending RO events), in addition to an antenna dedicated to POD
c) high immunity to on-board interference from other on-board instruments or spacecraft sub-systems
d) minimisation of system noise, to reduce thermal noise errors (limiting temperature profile accuracy in the upper stratosphere), cycle slip probability and of loss-of-lock thresholds
e) USO with Allan deviation better than 10^{-12} over 1 s to 100 s intervals to support occultation data processing based on single differencing (which removes the errors due to the transmitter clock instabilities but not those caused by the USO)
f) stringent requirements on the stability of the transfer function of the antenna and RF front-end and in particular on gains and group delays, in the tough spacecraft environment (e.g. antennas see wide temperature excursions)
g) tracking loop design optimised on the basis of models of the 'modulation' effects by the atmosphere on the GNSS signals (e.g., because of weather fronts) and of system specifications set in terms of refraction angle error in a given bandwidth
h) flexible and robust implementation of asynchronous software tasks with stringent time constraints using an off-the-shelf real-time operating system validated for the specific space processor
i) joint development of space equipment and ground processing, in order to maximise refraction angle recovery performance through optimal matching
j) carrier phase estimation as a (properly filtered) combination of the model phase (from PLL NCO) and the phase error (PLL input), to preserve the full information bandwidth
k) accurate amplitude signal estimation, to enable the recovery of the atmospheric Doppler shift even in the presence of multiple paths through the troposphere or of diffraction effects caused by large refractivity gradients
l) acquisition strategies tailored to different events (e.g. rise RO events require rapid acquisition of low-SNR, uncertain signal)
m) low-loss semi-codeless tracking to cope with GPS anti-spoofing (ESA patent)
n) capability to sample code-demodulated signals for which closed-loop tracking is impossible (e.g., when the signal path crosses the low troposphere in the tropics), in a 'open-loop mode' based on an on-board model of the Doppler generated by the atmosphere
o) stringent requirements on calibration and verification of the performance of the instrument and of the associated ground processing
p) high in-orbit availability, implying space qualified (e.g. radiation-tolerant) components and qualified development processes (only a short outage time to recover from radiation-caused resets is allowed)
q) high reliability over specified lifetime (> 5 years for GRAS on MetOp)
r) full observability of the instrument operation via telemetry and re-programmability by telecommands.

The principal building blocks of the instrument are shown in the block diagram of Figure 4. The instrument contains three complete receiver chains, each consisting of a dual frequency antenna, a close-by Radio Frequency Conditioning Unit (RFCU), and a central GRAS/GPSOS Electronics Unit (GEU).
One receiver chain with a hemispherical-coverage antenna is dedicated to on-board navigation and to POD within the ground processing. Two channels are dedicated to the dual-band carrier phase RO measurements, in the directions of the satellite velocity and in the opposite direction. Each receiver chain is capable of tracking several satellites. GRAS is equipped with 12 dual-band channels. GPSOS, which also provides electron density measurements in the ionosphere and therefore must track the SVs for longer periods, has 16 dual-band channels. Three complete flight sets of the GRAS instrument are presently in production at SE.

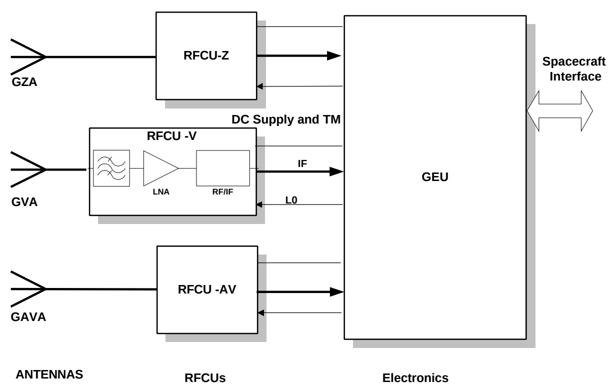

Figure 4: Occultation Instrument Block Diagram

The GRAS system performance is specified in terms of refraction angle accuracy and is summarised in Table 4. Table 5 provides some derived key electrical specifications.

Table 4 GRAS System performance summary

Parameter	Performance
No of occultations	500 /day
Measurement range	1 – 80 km
Refraction angle error (Including external sources)	< 1.0 µrad or 0.4% (2σ) {5 –80 km}
Altitude resolution	< Fresnel zone {1.5 – 0.2 km}
Sampling rate	up to 50 Hz up to 1 kHz raw sampling mode
Navigation carrier phase L1 & L2 (including multipath)	<2 mm std @ high elevation <5 mm std @ low elevation
Life time **GRAS** **GPSOS**	5 yrs in orbit 7 yrs in orbit
Reliability **GRAS** **over life** **GPSOS**	0.80 0.86

Table 5 Instrument performance aspects

Parameter	Performance
USO Allan variance	$<10^{-12}$
USO Stability	$<10^{-11}$ K^{-1}
Occultation antenna gain	>10 dBi (±55° azimuth)
System noise temp.	<300 K Navigation <420 K Occultation
Doppler accuracy	<1 mm/s (2σ)
Bending angle accuracy (Introduced by instrument)	<0.5 urad or 0.2% (2σ) {5 –80 km}

Performance analyses show that the USO stability drives the accuracy of atmospheric measurements, while good signal-to-noise ratio (SNR) is essential to reach the measurement range at low altitudes. High-gain (> 10 dB) antennas are needed to achieve the required SNR. The instrument can support a 30 dB attenuation due to atmospheric attenuation and defocusing. Rapid acquisition algorithms are implemented to capture the rise RO events early enough to cover the lower altitude range.

The L2 tracking may be lost in the troposphere i.e. altitudes below some 10 km, during set events, and not be acquired during the rise events. However, the L1 measurements are sufficient, since the effect of the ionosphere can be extrapolated from models and from the dual-band data collected in the upper atmosphere.

This loss of L2 tracking is caused partly by the lower EIRP, but also by anti-spoofing: the instrument uses a semi-codeless tracking technique to measure L2 carrier phase, but this inflicts a large SNR loss (exceeding 10 dB at carrier-to-noise density ratios around 50 dBHz and non-linearly varying with the SNR itself).

To extend the height range of the final data products, a so-called raw sampling mode is used. When loss-of-lock occurs (for instance, because of large refractivity gradients caused by temperature inversions), the (complex) correlator outputs are recorded at a relatively high rate (up to 1 kHz), until loss of lock is detected in the C/A code tracking loop (the most robust one). During this period of ‘open-loop’ operation for carrier phase measurements, the change of Doppler caused by the changing geometry and by the atmosphere is compensated so as to maintain the sampled signal in the correct frequency window and continue C/A code tracking, with a tracking loop bandwidth of 1 Hz, for as long as possible. . The on-board model Doppler trajectory is also recorded, to aid the reconstruction of the signal phase and amplitude in ground processing.

Figure 5 shows the propagated errors in refraction angle, refractivity, pressure and temperature as functions of altitude. The measurement bandwidth, i.e. the data filtering, expressed as vertical resolution, is used as parameter. Note that, while the refraction (bending) angle accuracy is highly dependent on the resolution, this dependence almost vanishes for refractivity and higher level products. The reason for this is that the noise spectral contribution increases at the higher frequencies. The refractivity is obtained via an Abel transform that behaves almost like an integration, hence decreasing the contributions from high frequency components. Such components are even more filtered for pressure and temperature.

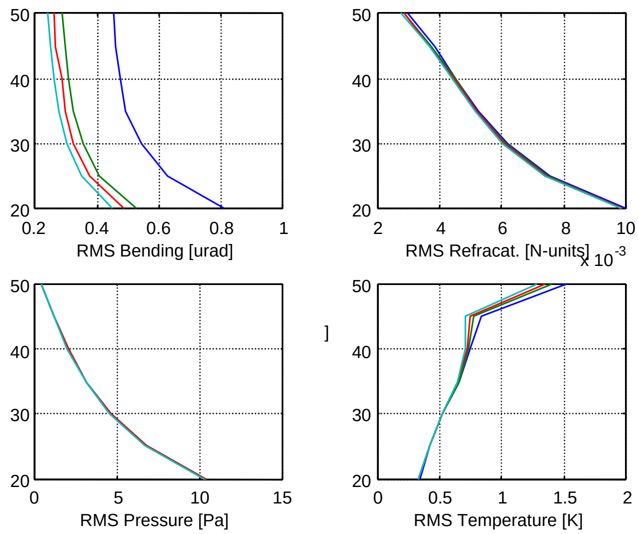

Figure 5: Retrieval errors (2s) vs. altitude (in km), with vertical resolution (measurement bandwidth) as parameter.

Legend:
blue - 0.5 km
green - 1.0 km
red - 1.5 km
magenta - 3.0 km

A total of three complete flight sets of the GRAS instrument have been ordered and are presently in production at Saab Ericsson Space.

ANTENNAS

The RO array antennas (Figure 6) comprise 18 dual-band radiating elements and have the maximum gain tailored to the Earth horizon (Figure 7), where the largest atmospheric absorption and defocusing are experienced. The coverage is wide in azimuth (110°) to capture all useful RO events (more than 500 per day with GPS). For the GPSOS version the elevation coverage is extended to include most of the ionosphere. The zenith-pointing navigation antenna is a wide-coverage antenna optimised for low multipath. For all antennas, the radiating elements are based on circular rings. The patterns of the RO antennas mounted on the satellite will be known to better than 0.5 dB in gain and approx. 3° in phase.

Figure 6: Occultation antenna (size: 86 cm by 48 cm).

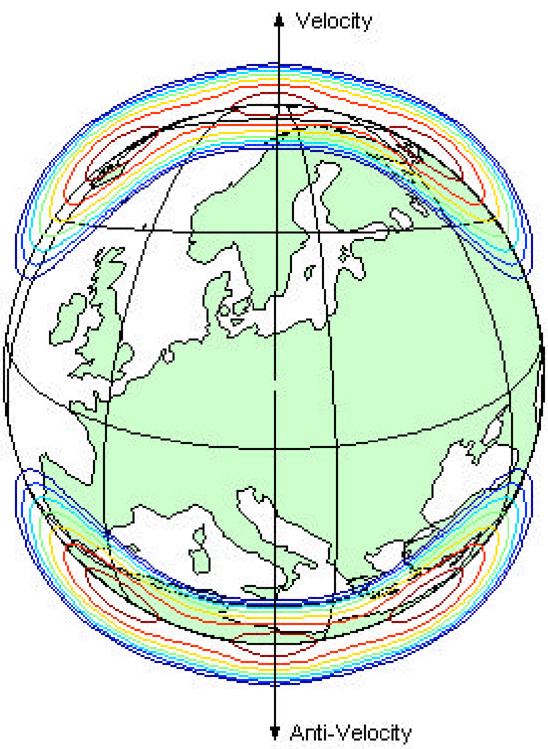

Figure 7: Occultation antenna patterns, seen from the receiver.

Legend:
Peak level 11 dB
steps of 1 dB

FRONT-END

The main purpose of the RFCU is to locate the low noise amplifiers, with 0.7 dB noise figure, as close as possible to the antennas in order to minimise the system noise figure and to ensure good rejection of on-board radiated interference. The RFCU (Figure 8) contains sharp selection filters for each band, protecting the receivers against the severe RF environment. A transmitter on MetOp outputs 10 W only 20 MHz below the L1 band. This signal is suppressed by more than 95 dB in the RFCU (Figure 9).
The RFCU includes electronics for down-converting the signal to intermediate frequency (IF) in the band 150 - 200 MHz. The IF signal is then routed to the GEU on a single coaxial cable. Special circuit and components solutions have been adopted to minimise low group delay and amplitude sensitivity to temperature changes.

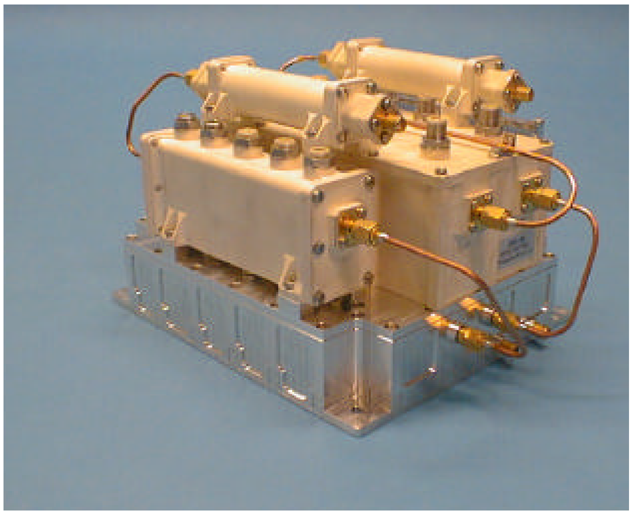

Figure 8: GRAS Radio Frequency Conditioning Unit. Its size is driven by the pre-selection coaxial-cavity filters.

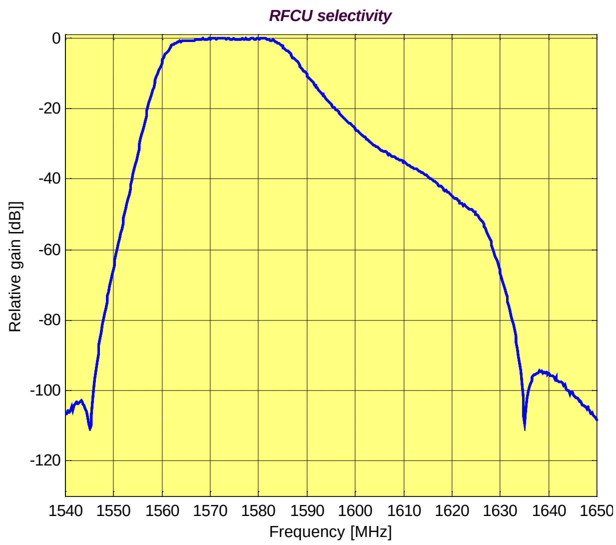

Figure 9: RFCU selectivity for GPS L1 band.

CENTRAL ELECTRONICS

The main GEU blocks are the three receiver chains, digital signal processor (DSP), spacecraft interface (SCIF), frequency generator, ultra-stable oscillator and DC/DC converter (Figure 10). These electronics are housed in a single box (Figure 12), using five plug-in PCB boards.

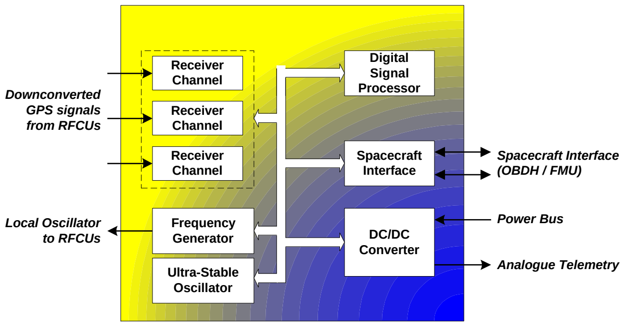

Figure 10: GEU Block Diagram.

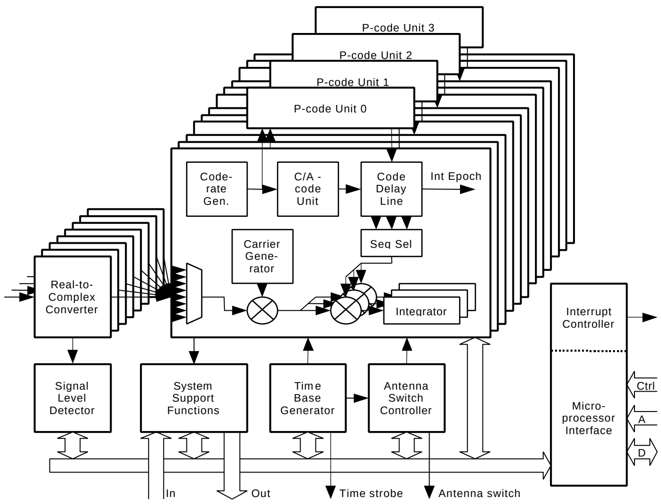

Figure 11: Block diagram of the AGGA ASIC.

In each receiver chain the IF signal is band-pass sampled by an 8-bit analogue-to-digital converter operating at approximately 140 MHz. The signal is then digitally down-converted, filtered with FIR filters and re-quantised to match the 2-bit AGGA input format in a dedicated ASIC. The digital nature of the second down-conversion and associated filtering removes errors caused e.g. by filter instabilities. The wide-band, multi-bit scheme ensures low SNR loss (total receiver implementation loss for GPS L1 carrier phase < 1.5 dB) and further interference resistance. A stable performance is achieved across a wide temperature range. The baseband signals are finally input to a set of AGGA chips [10], where a bank of complex (I/Q) correlators de-spreads them. The AGGA block diagram is shown in Figure 11. Each chip provides four dual-band channels (or 3 single-band channels in place of each dual-band channel) with a total of 36 complex correlators, with on-chip support for: correlator slaving (for rapid acquisition), correlation with sub-chip spacing, codeless and semi-codeless tracking, and operation with different systems (GPS, GLONASS). The AGGA gate count is of about 200 kgates.

The DSP runs the data processing algorithms (including those for DLL, FLL, and PLL operation), as well as the instrument control. The core of the DSP board is the TSC21020E, a space-qualified radiation-tolerant version of Analog Devices ADSP21020 manufactured by ATMEL/Temic [13]. The processed and formatted data is finally output to the spacecraft data bus.

The USO-driven frequency generator provides each RFCU with a local oscillator (LO) signal and the receiver chains in the GEU with sample clocks.

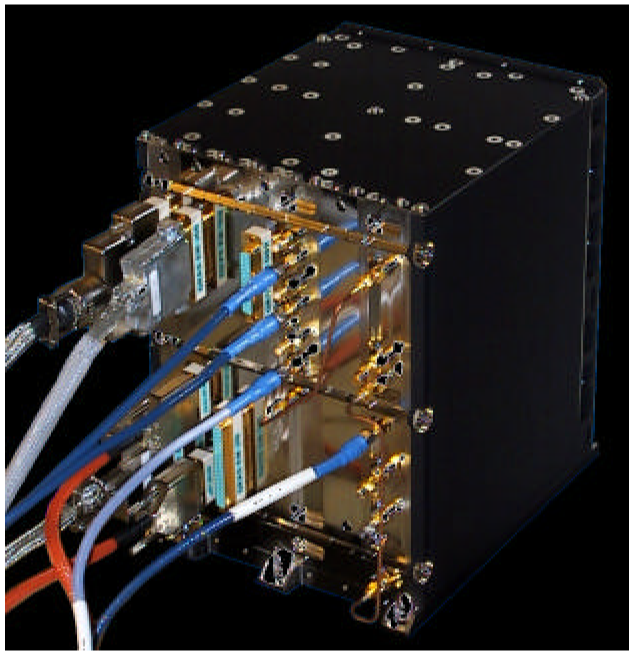

Figure 12: GRAS Electronics Unit.

SYSTEM EVALUATION

The GRAS work includes also a Ground Processing Prototype (GPP) in order to validate the data flow and the algorithms that generate the data products. The GPP functionality includes:

- Data sorting, reformatting, time-alignment
- Corrections/calibrations for equipment temperature variation and antenna angle of incidence
- Ingestion of fiducial station data for clock correction
- Resolution of phase profile data for cycle slips
- Processing data for retrieval of refraction angles profiles, using both geometrical optics inversions and inversions based on physical optics back propagation.

A system simulation software has also been developed to:

- Simulate the signal received by the instrument, including RO geometry and atmospheric propagation effects
- Simulate instrument generated errors and accompanying source data (e.g. temperature)
- Simulate fiducial station data for clock correction
- Evaluate the end results

FUTURE DEVELOPMENTS

GRAS is a first-generation space-qualified instrument dedicated to atmospheric sounding by means of GPS RO. It is accommodated on a large satellite with severe RF environment, driving the design to robustness. The second-generation GRAS instruments will also be located on micro-satellites, flying in constellations. This will require optimised size, mass and power consumption in order to fit the tighter accommodation on these satellites.

SE is engaged in ESA studies aiming at this miniaturisation, covering all the aspects of the receiver, including: active antenna beam-forming and new radiating elements (to reduce the array size); higher functional integration into the AGGAs (more channels per AGGA, on-chip processor core to reduce the load of the external processor, support to fast signal search and acquisition), exploiting advances in space ASIC technology that allow to integrate more than one million gates; use of Galileo signals; new RF front-end design, based on the use of low-power ASICs (integrating all functions but LNA and filtering). The latter is the subject of a dedicated development, which builds on advances in analogue CMOS technology spurred by mobile communications.

The on-board algorithms for acquisition and tracking is based on the current knowledge of the signal conditions during RO measurements. Improved models of the atmospheric modulation and mission data will allow for further optimisation of the signal acquisition strategies and tracking loop parameters.

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